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Abstract

The application of crosshole EM methods through steel well-casing was investigated in theoretical, laboratory and field studies. A numerical code was developed that calculates the attenuation and phase delay of an EM dipole signal propagated through a steel well casing lodged in a homogeneous medium. The code was validated with a scale model and used for sensitivity studies of casing and formation properties. Finally, field measurements were made in an oil field undergoing waterflooding.

Our most important findings are that 1) crosshole surveys are feasible using a well pair with one metallic and one non-metallic casing. 2) The casing effect seems be localized within the pipe section that includes the sensor. 3) The effects of the casing can be corrected using simple means and 4) crosshole field data that are sensitive to both formation and casing were acquired in a working environment.

Introduction

The goal of crosshole electromagnetic induction surveys is to map the resistivity distribution between wells. Recent surveys were successful in oil field reservoir characterization, steam flood tracking and salt water flood monitoring (Wilt et al., 1995; Alumbaugh and Newman, 1995). Measurements have been made at well spacings up to 300m and data are interpreted using 2-D and 3-D models (Torres and Habashy, 1993; Alumbaugh and Newman, 1995).

Successful crosswell field surveys have applied audio and radar frequency signals (1 kHz -20 MHz) through uncased or non-metallic cased boreholes. Unfortunately, steel-cased wells are most often used in the petroleum industry and these pose serious problems to crosswell EM surveys, due to the high attenuation and phase delay. Extending the crosshole EM technique to steel-cased wells is an important objective of our research because it dramatically broadens the use of this technique.

Augustin et al. (1989) and Wu and Habashy (1994) showed that the attenuation due to steel well-casing prohibits measurement above a few hundred Hz. Even at lower frequencies the casing effect is considerably stronger than the formation effect. Recent field surveys showed that good quality low frequency magnetic field data could be collected in a steel-cased well if a surface-based transmitter or a powerful borehole transmitter in a non metallic well is used (Wilt and Ranganayaki, 1989; Wilt et al. 1991). As yet, however, no successful crosshole EM measurements have been reported when both source and receiver tools were placed in steel-cased boreholes.

Crosshole field surveys using one steel and one fiberglass cased well could have significant impact in the petroleum industry. Potential application could be the monitoring of waterfloods and the evaluation of older oil reservoirs for missed or bypassed oil. For example, many older oil fields have numerous steel-cased production wells and a few fiberglass-cased wells used for monitoring water induced resistivity changes with induction logs. Crosshole measurements could be effective from the fiberglass well to any steel-cased well located within a few hundred meters. These surveys would provide a resistivity cross-section between the wells, or if measurements are made over time, a view of subsurface changes due to water or steam flooding.

In 1994 the UC/LBL subsurface EM consortium began a three year program to investigate the effect of steel-casing on crosshole EM data with the goal of developing realistic models of well casing and of collecting a set of crosshole data through a steel-fiberglass cased well pair. The ultimate goal is to develop a means to separate the casing and formation effects. In this short paper we will describe the progress made during the past two years.

Numerical and Scale Model Studies

The effect of metallic well casing on crosshole EM signal was examined with the aid of a computer code described by Augustin et al. (1989) and later modified by Uchida et al. (1991). The code allows for the calculation of the frequency domain electromagnetic field within and exterior to a uniform conducting pipe in a homogeneous conducting whole-space. An electric or magnetic dipole (VMD) source may be placed within or exterior to the pipe. The code has been validated with scale models and we have used it to study the influence of the casing on the formation signal as a function of frequency.

Typical results for standard oil field well casing are shown in Figure 1. Here we have plotted the field amplitude and phase for a VMD receiver within a typical oil field casing using a VMD source located within a second nonconducting well casing 89 meters away at the same vertical level. The fields are plotted as a function of frequency for casing in a free-space environment and within a uniform formation resistivity od 3. ohm-m. The open squares plotted on the figure are field results, these will be described further below.

The plots clearly show the attenuation and phase shift due to the metallic casing. Above 100 Hz the casing attenuates the signal by more than a factor of 100; above 500 Hz it is more than 1000 and too large to collect useful data. The field curves for casing with and without formation merge at low frequencies but become distinct above a few tens of hertz. They show the largest deviation on the log-log plot at several hundred Hertz but note that the largest absolute difference between fields with and without formation is at frequencies between 10-50 Hz. This suggests that to obtain direct formation properties is better to operate at frequencies, between 10 and 50 Hertz, where the casing effect is relatively small and the formation is still distinguishable. For monitoring resistivity changes it is better to operate at several hundred hertz where the percentage change is largest and the affect of the casing is large but unchanging with time.

Scale model measurements were made to validate the above code as well as to test the effect of segmented casing and casing collars on the fields inside of the pipe. These measurements, made in 2 m pipe segments, fit numerical models for infinitely long pipe of the same properties within two percent. This suggests that the casing effect is quite local, most likely due to the pipe immediately surrounding the sensor. Other numerical and scale model results suggest that for distant sources the formation and pipe affects are separable by simple arithmetic means (Augustin et al., 1989). The steel casing therefore primarily acts as a filter and its affect may be removed by knowing the filter response.

Field Studies

Mobil is waterflooding the Pliocene Monterey diatomites at the Lost Hills oil field near Bakersfield, California for improved oil recovery. The diatomites form a series of oil and gas reservoirs in onshore and offshore central California with a total potential of more than 10 BBbl's Kovscek et al. 91995). The recovery rates from water injection have ranged from 8-12 percent, far below the rate for many water floods, this may be due to water channeling and reservoir by-pass. For this reason Mobil has installed a series of fiberglass cased observation wells near the water injectors to monitor the water-swept intervals using repeat induction resistivity logs.

In 1994 we began a collaborative project with Mobil to test the crosshole EM technique for mapping the resistivity structure between wells and to track resistivity changes due to the water injection. Fiberglass monitoring well 003 is located 10 m from the water injector 034 and 89 m from steel-cased production well 125-4. Induction resistivity logs in 003 show that the average resistivity of the diatomite is 2.5 ohm-m, varying from 1.5 and 4 ohm-m in the production interval from 1800-2200 ft. In addition, repeat induction logs show that the water injection has decreased the resistivity from 20 to 40 percent (Figure 2a).

The initial crosshole experiment had two objectives; the first was to determine if the crosshole data reflect characteristics of the well casing in 125-4. The second was to characterize and remove the casing effect and interpret the adjusted data. Initially, measurements would be confined to a single fiberglass/steel well pair, but if the initial surveys are successful they will be expanded pattern wide and repeated over time to monitor movements of the water front.

For the first part of the experiment we deployed the Schlumberger "Electromagnetic Thickness" (METT) logging tool in the steel-cased well. Although this device was designed to measure the thickness of steel casing it also provides the relative magnetic permeability of the different pipe segments. The electrical conductivity of the casing is not easily obtained from this log, but experience at Schlumberger indicates that this parameter does not change much from pipe to pipe whereas the permeability can change greatly. The METT log was measured in borehole 125-4 prior to the crosshole EM measurements.

Crosshole EM measurements were made in 1995 using equipment described in Wilt et al., 1995. We deployed our transmitter in fiberglass well 003 and the receiver in borehole 125-4 for a series of experiments. Based on the work described above we assume 1) the attenuation and phase delay is due only to the casing segment encompassing the receiver tool, and 2) the casing and formation effects are separable. This means that if we determine the casing properties for the pipe that contains the receiver tool we may correct the field data for this effect.

For the initial test we positioned both source and receiver tools at the same vertical level and adjusted the frequency of the transmitter beginning at the lowest frequency detectable with our receiver (20 Hz) and increasing until the signal was undetectable (about 500 Hz). These soundings were made at 10 different levels, corresponding to different casing segments and subtle differences in formation resistivity. The sounding data were found to repeat over time to about 3 percent.

In Figure 1 we show a crosshole frequency sounding from a depth of 1670 ft at Lost Hills. The plot shows field measurements and model data corresponding to the casing effect with and without a formation effect. The model data were calculated with the code described above; casing parameters were obtained by using the METT log for the thickness and by trial and error fitting of the lower frequency section (< 50 Hz) of the crosshole soundings measurements using reasonable estimates for the permeability and conductivity. At these lower frequencies the calculated models with and without formation effects agree to within a few percent. We found that we could adequately fit soundings at other levels simply by adjusting the permeability and thickness of the casing model according to variations observed in the METT log.

Next, we measured a series of profiles where we fix the receiver tool at one position in the steel well, and move the transmitter over a 150 m interval in the fiberglass well. We collected these profiles using a frequency of 200 Hz for receiver position from 1600 to 1800 ft. These data repeat to between 2-10 percent.

Assuming that the casing and formation effects are separable we can interpret these profiles by adjusting the profile response for the free-space casing model using parameters for the casing segment enclosing the receiver. For a single frequency profile this amounts to a single adjustment for the amplitude and phase. For example for EM profile 1670 the 200 Hz casing adjustment is a factor of 86 in amplitude and a phase shift of 350 degrees (Figure 1).

After correcting the profile for the casing, the data may then be interpreted by conventional means. For profile 1670 we applied a least squares inversion to fit the field data to a simple two layer model; the results are shown in Figure 3. The final model agrees reasonably well with the induction resistivity log in this very uniform formation.

Conclusions

The result achieved thus far in this research program are promising but our work is far from complete. We need an accurate means to characterize the well casing. This may be achieved with a tool similar to the METT device, but one that provides individual estimates of casing conductivity, permeability and thickness. Next, we need field tools optimized for the low frequencies and the steel casing environment.

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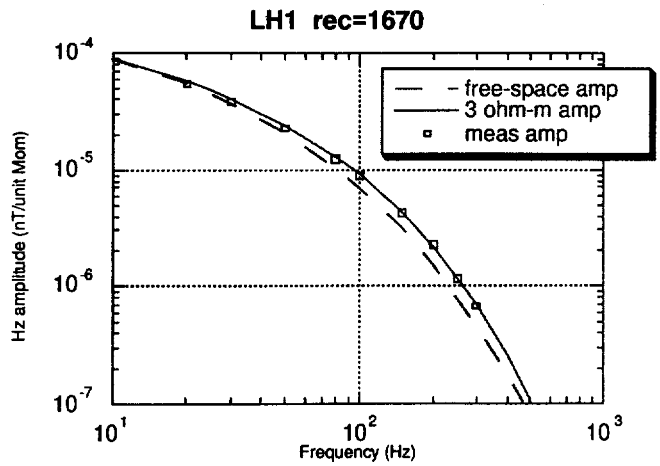

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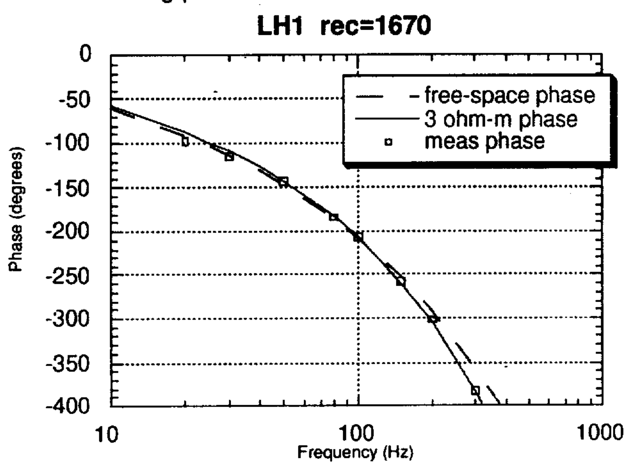

Figure 1 Crosshole frequency soundings through steel-casing. Plotted points are field measurements.

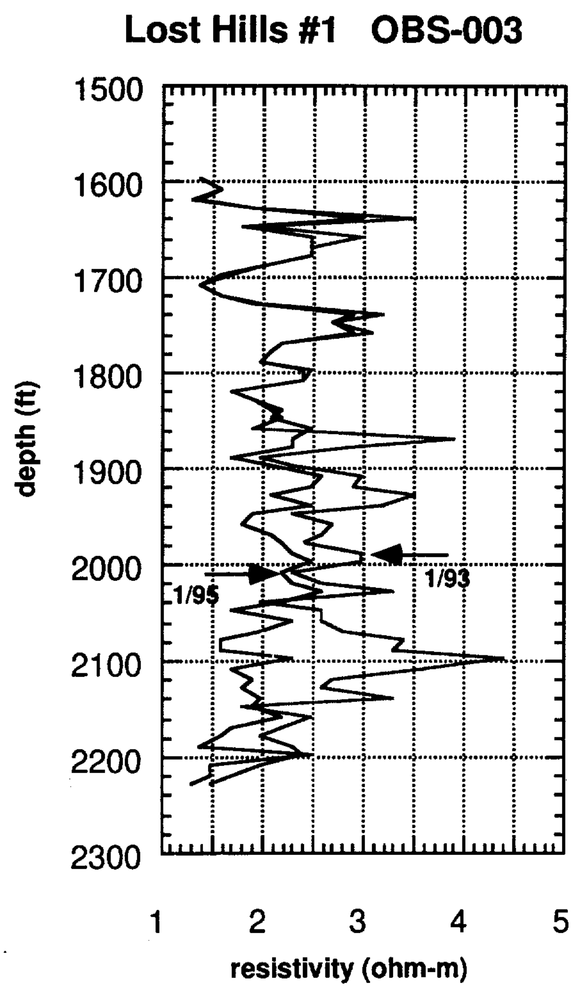

Figure 2 Borehole induction resistivity log in the fiberglass observation well used for the field experiment.

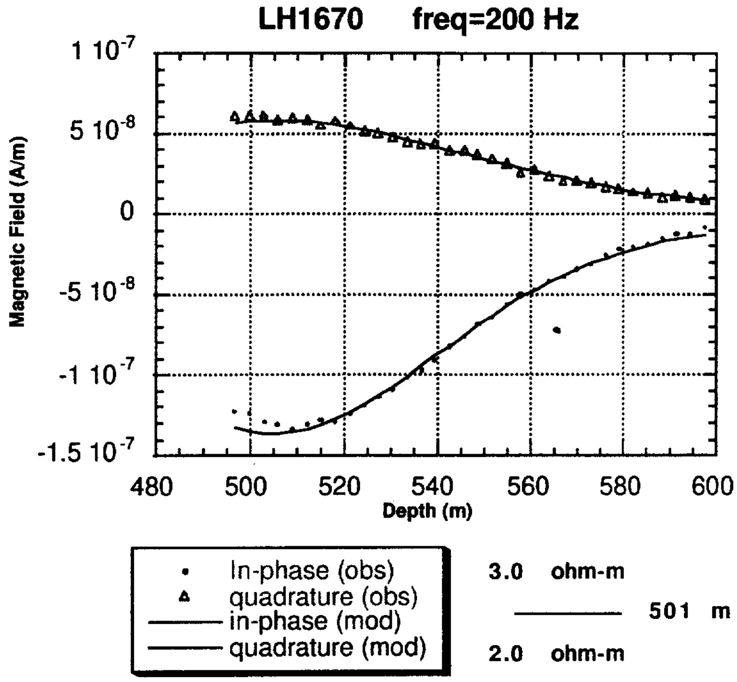

Figure 3. Crosshole EM profile at the Lost Hills field The data have been adjusted to compensate for the casing affect in the receiver borehole. The solid curves are for the two layer model shown in the Figure.